PENTAQUARK UPDATE

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In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov *et al.* proposed the existence of a low-mass anti-decuplet of pentaquark baryons, with spin 1/2 and even parity, and provided specific estimates for the masses and widths. In particular, they predicted an exotic positive-strangeness baryon, Θ^+, consisting of the quark combination $uudd\overline{s}$, with a mass of about 1530 MeV and a width of 15 MeV or less. In 2003, from an analysis of $\gamma n \to nK^+K^-$ data taken in 2000–2001 at the LEPS facility in Japan, Nakano *et al.* reported the observation of a narrow nK^+ peak at a mass of 1540 MeV, with a quoted significance of 4.6 standard deviations (σ). (See Data Listings and references for the $\Theta(1540)^+$ following this note.)

This remarkable result was followed, over the next year, by reports from nine other experiments, all different and each claiming to observe a narrow nK^+ or pK^0 peak at a mass between 1522 and 1555 MeV, with a confidence level of 4 σ or more. Half of these signals came from photoproduction experiments (with incident real or virtual photons), and the others came from other production processes at a variety of energies. As remarked below, there were questions about some of these observations; but, given the weight of positive supporting evidence reported by early 2004, this *Review* assigned a 3-star status to the Θ^+ in its 2004 edition.

Further evidence in support of pentaquark states seemed to come from the claimed observations of a doubly-charged $ssdd\overline{u}$ state at 1862 MeV, and a neutral $uudd\overline{c}$ state at 3099 MeV. (See Data Listings and references for the $\Phi(1860)$ and $\Theta_c(3100)^0$ following this note.) However, there has been no confirmation of either of these states, with several subsequently reported high-statistics searches showing zero signal. There is thus no credible evidence that either of these positive observations is more than a statistical fluctuation, and they do not provide support for the reality of the Θ^+.

As pointed out in the 2004 *Review*, the evidence for the Θ^+, as statistically compelling as it seemed, had some problems. Backgrounds appeared to be underestimated; cuts seemed specifically designed to make signals look as convincing as possible; mass-peak locations varied from experiment to experiment by much more than would be expected from a narrow resonance; published data samples of low-energy kaon and pion inelastic interactions showed no indication of a signal; and charge-exchange and partial-wave analyses of KN interactions required an extremely small Θ^+ width ($\leq$ 1–2 MeV). It was clear that further confirmation with better statistics was essential.

In fact, subsequent to Nakano *et al.*'s initial paper, about ten different searches for the Θ^+ in a variety of reactions and energies have reported null results, many with high statistics (see the Data Listings). Some of these involve higher energies or reactions different from those that produced positive results, and therefore, while providing no support for these results, may not directly contradict them. Indeed a significant amount of theoretical activity has been devoted to trying to devise selective pentaquark production mechanisms that might be consistent with both the positive and the negative observations. However, it is worth noting that conventional low-mass resonances, such as $\Lambda(1520)$, are observed at practically all energies above threshold, from any reaction that leads to their decay products.

Two of the negative papers, namely those of the Belle Collaboration (Mizuk *et al.*) and the CLAS Collaboration (Battaglieri *et al.*), have particular impact, because they both involve energies and reactions that almost repeat experiments that had given positive results. Mizuk *et al.*, using data from their e^+e^- B-physics experiment, report an analysis of K^+n charge exchange taking place in the material in the inner part of the BELLE detector, where the incident K^+ arises from charm-particle decay near the e^+e^- collision point. Measuring K^0p final-state masses, they see no enhancement near 1540 MeV, in disagreement with the charge-exchange results of the

Diana Collaboration (Barmin *et al.*). Mizuk *et al.* quote a Θ^+ width upper limit of 0.64 MeV at a mass of 1539 MeV (the mass reported by Barmin *et al.*), to be compared with the actual estimate of 0.9 MeV made from the Barmin reported signal. (This upper limit is somewhat mass-dependent, going as high as 1 MeV for some values between 1520 and 1550 MeV.) Thus, while the BELLE results do not, for the proper choice of mass, statistically contradict the DIANA results, they show no evidence for the signal reported by DIANA.

Battaglieri *et al.* (CLAS Collaboration) basically repeat with greatly increased statistics the photoproduction measurements of Barth *et al.* (SAPHIR Collaboration) using the reaction $\gamma p \to K^0 K^+ n$. Whereas the SAPHIR Group had reported a 4.8 σ signal in the $K^+ n$ mass spectrum, the new CLAS experiment shows no signal at all. Indeed the upper limit on the ratio of Θ^+ to $\Lambda(1520)$ production from CLAS is more than a factor of 50 lower than the value claimed by the SAPHIR group. This result completely negates what appeared to be one of the strongest of the positive observations. Combined with the other negative reports, it leaves the reality of the Θ^+ in great doubt.

All the results quoted so far are from papers either published or submitted and approved for publication. However, for completeness, it is worth mentioning that, in addition to its high-statistics γp experiment just discussed, the CLAS Collaboration has reported, but not yet published, results for a high-statistics $\gamma d \to n K^+ K^- p$ experiment in the same energy range. These results were first presented by Volker Burkert at the 2005 Lepton-Photon Conference in Uppsala, and have subsequently been discussed at other meetings. The statistics reported are about six times those of the previously published CLAS paper on the same reaction at the same energy (Stepanyan *et al.*) in which a signal with a significance above 4.6 σ was claimed. In the new work, no signal is observed. The CLAS Collaboration has reexamined its earlier work, using a background shape based on the new data, and concludes that the background in the earlier sample was underestimated, and that the signal, now at just the 3 σ level, probably is a statistical fluctuation.

To summarize, there has not been a single high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

It is perhaps useful to comment on how it is that so much apparent statistical strength was claimed for a set of results that, in retrospect, do not appear to be correct. One obvious problem was the large variation in the locations of the observed mass peaks ($\sim$30 MeV) for what had to be a very narrow resonance; thus, the various experiments were not truly confirming one another. Another concern arises from the uncertainties in background shapes which perhaps were not adequately reflected in the large confidence levels claimed. Other technical problems may have involved resonance reflections and "ghost tracks." The main issue, however, concerns the burden of proof required in the confirmation of a major new discovery. Here, "burden" applies solely to the work of the confirming authors, independently of the existence of a discovery paper. Should the burden be as high as for the discovery itself? What should be the burden if there have already been several claimed confirmations? It seems unlikely to us that some of the confirming results for the Θ^+ would have been published had there not been a discovery claim already on the table. We believe that the burden of proof for the confirmation of an important new result should be about as high as for the original claim of discovery. Only then can one hope to separate the influence of the original discovery from the supposedly independent results of the confirming papers and convince oneself that the confirmation adds significantly to the confidence in the discovery.

References

1. D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. **A359**, 305 (1997).